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Climate impacts on hydropower in Colombia: A multi-model assessment of power sector adaptation pathways

Santiago Arango-Aramburo[a,*], Sean W.D. Turner[b], Kathryn Daenzer[c], Juan Pablo Ríos-Ocampo[a], Mohamad I. Hejazi[b,d], Tom Kober[e,f], Andrés C. Álvarez-Espinosa[g], Germán D. Romero-Otalora[g], Bob van der Zwaan[e,h,i]

[a] Decision Science Group, Facultad de Minas, Universidad Nacional de Colombia, Colombia
[b] Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD 20740, USA
[c] Department of Geography & Environment, Boston University, Boston, USA
[d] Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD 20740, USA
[e] Energy research Centre of the Netherlands (ECN-TNO), Energy Transition Studies, Amsterdam, the Netherlands
[f] Paul Scherrer Institut, Laboratory for Energy Systems Analysis (LEA), Villigen, Switzerland
[g] Departamento Nacional de Planeación, Bogotá, Colombia
[h] Johns Hopkins University, School of Advanced International Studies (SAIS), Bologna, Italy
[i] University of Amsterdam, Faculty of Science (HIMS), Amsterdam, the Netherlands

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ABSTRACT

Climate change is likely to affect water availability and therefore hydropower generation in many regions of the world. In drying regions, hydropower generation may be impaired, creating a need for new power investments that would otherwise have been unnecessary. In this study we apply two partial equilibrium models (GCAM and TIAM-ECN) and two general equilibrium models (MEG4C and Phoenix) to identify possible pathways of power sector adaptation for Colombia under climate change. We adopt two GCM projections that deteriorate hydropower generation over the next three decades, and simulate each for two radiative forcing scenarios (RCP8.5 and RCP4.5). Relative to Colombia's projected power demand growth over the coming decades, losses in hydropower generation are marginal. Nonetheless, climate-driven losses in hydropower must be compensated by alternative technologies´expansion, which vary significantly across models. When climate policy is implemented (RCP4.5), three distinct expansion pathways emerge: increased solar and wind energy (TIAM-ECN); significant power demand reductions (Phoenix and MEG4C); and increased fossil resources with carbon dioxide capture and storage (GCAM). We show the need to explore the tradeoffs/synergies among alternative expansion pathways and their potential impacts on other sectors (e.g. water and land), and for effective policies to incentivize their adoption in Colombia.

1. Introduction

Climate change is expected to manifest in significant drying across many regions of the world (Arnell, 2004; Schewe et al., 2014; Haddeland et al., 2014), raising the potential threat of reduced water availability for power generation in heavily exploited river basins (van Vliet et al., 2012; Bartos and Chester, 2015; Lumbroso et al., 2015). The main generating technologies likely to be affected are hydropower plants, which depend on river flows to fill dams and drive turbines, and thermal plants, which often use fresh water for cooling (Kyle et al., 2013; Macknick et al., 2012). In regions where reduced water availability impairs power generation, there will be a need to either reduce energy demands or install new generating capacity—the latter implying new power plant investments and possibly increased CO_2 emissions depending on the replacement technologies deployed (Spalding-Fecher et al., 2017; Turner et al., 2017b; Parkinson and Djilali, 2015). Regions that depend heavily on hydropower will need to understand these potentiual impacts and their associated implications for power sector investment planning (Lucena, 2018; Turner et al., 2017a).

Colombia is one such case. Hydropower in Colombia accounts for approximately 70% of total installed capacity (XM, 2017). Most is located in the country's mountainous regions, where there is substantial uncertainty as to how warming will affect precipitation and water availability (Turner et al., 2017a). With the remaining 30% of

* Corresponding author.
E-mail address: saarango@unal.edu.co (S. Arango-Aramburo).

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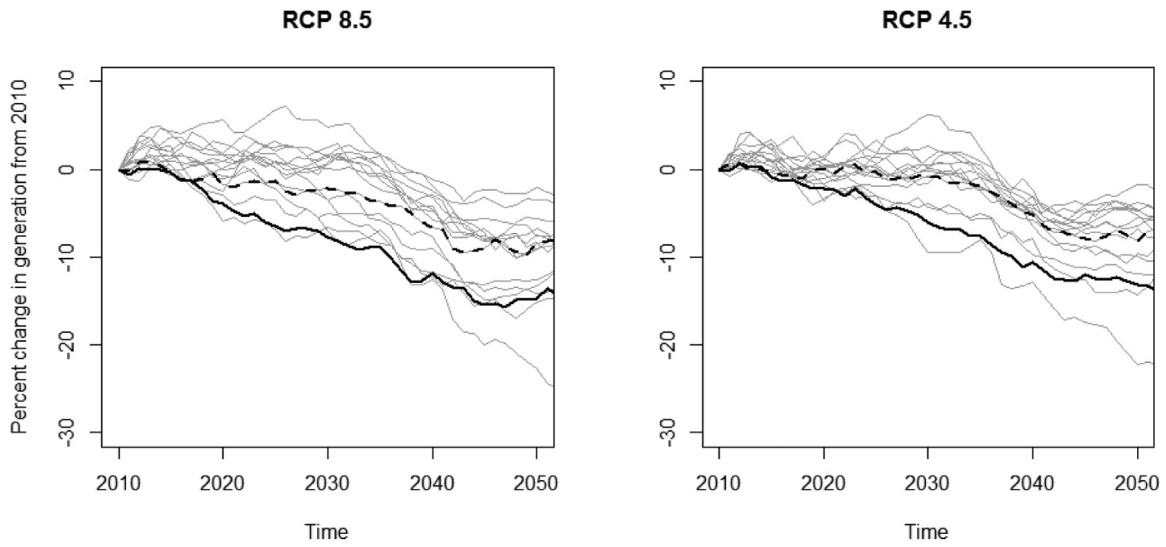

Fig. 1. Climate change impacts on hydropower generation in Colombia: CNRM_CM5 (dark, solid line), CESM1_BGC (dark, broken line), ACCESS1_0, BNU_ESM, CanESM2, CESM1_CAM5, CCSM4, CMCC_CM, CSIRO_Mk3_6_0, GFDL_CM3, GFDL_ESM2G, GFDL_ESM2M, GISS_E2_R, FGOALS_g2, FIO_ESM, IPSL_CM5A_LR.

Colombia's power capacity made up by thermal plants, and with limited potential sites for new hydropower developments, Colombia will be required to expand and diversify its power sector in the coming years and decades A highly diversified power sector is a plausible goal for Colombia given its significant and unexploited potential for wind and solar generation (Nieves and Hernández, 2016; Haubensak, 2011). These untapped resources present Colombia with unique opportunity to adapt its power sector to a drying climate in a way that would also help realize its commitments to reduce carbon emissions under the Paris Agreement (UNFCCC, 2015). On the other hand, Colombia could mobilize its massive, 6.3 billion ton coal reserve (UPME, 2016) by increasing coal-fired capacity. This would be a relatively cheap option, but would carry the potential risk of allowing emissions to rise if implemented without carbon capture and storage (CCS) technology. Given this spectrum of options, Colombia is currently seeking to identify pathways for power sector expansion and understand the associated impacts on costs of power delivery, emissions, and its economy.

In order to identify plausible pathways of power sector adaptation for Colombia, we simulate power sector response to losses in hydropower generation driven by a drying climate. We achieve this by forcing four distinct energy system models with General Circulation Model (GCM)-derived projections of hydropower generation under two Representative Concentration Pathways (RCPs) (van Vuuren et al., 2011). Each energy model is distinct in its structure and underlying data—so our multi-model approach enables us to trace power sector adaptation pathways to assumptions relating to energy technologies and their competitiveness by 2050. We demonstrate how these pathways of power sector adaptation could be used to assess possible impacts on emissions and the Colombian economy.

2. Materials and methods

2.1. Hydropower impact scenarios

We develop future hydropower generation scenarios for Colombia using a top-down climate impact assessment procedure. First, downscaled and bias corrected projections of temperature and precipitation from sixteen CMIP5 GCMs (monthly time series at 0.5° grid resolution – BoR, 2016) are used to force a Global Hydrological Model (GHM) to generate runoff. The GHM applied here is the Global Water Availability Model (GWAM) (Hejazi et al., 2014; Li et al., 2017), which simulates monthly runoff by tracking the soil water flux of each spatial grid. This runoff is then converted to streamflow using the River Transport Model (RTM) (Li et al., 2015), which applies a cell-to-cell routing scheme based on grid elevations (previous validation work using reanalysis climate data has demonstrated that dam models forced with gridded streamflow at this resolution can capture observed hydropower generation adequately for Colombia—see Turner et al., 2017a). Next, the technical, exploitable hydropower generation is estimated for each spatial grid containing existing and planned hydropower dams (technical, exploitable hydropower is potential generation after accounting for economic and environmental limits, as defined in Zhou et al., 2015). Aggregating across grids gives for each GCM a trajectory of hydropower potential for Colombia (in EJ), which is smoothed using a ten-year moving window. Smoothing ensures the capture of long-term trends in hydropower generation rather than the internal variability associated with given GCM realizations. Also, aggregating from monthly to annual estimates is necessary to ensure consistency with the resolution of the downstream energy models. Finally, total generation (EJ) is transformed to percentage change in production relative to 2010 and then superimposed onto Colombia's projected hydropower capacity expansion to 2050 (a similar overall approach is applied across multiple regions in Turner et al., 2017b).

This projection includes capacity and entry date of dams currently under construction in Colombia, including the major Porvenir II project (350 MW, expected for November 2018) as well as the Ituango project (2400 MW, staged expansion between 2018 and 2022). Ituango will be Colombia's largest power station. Since there is ambiguity regarding hydropower expansion beyond 2022, we assume a significantly slowed expansion rate of approximately 25 MW per year between 2022 and 2050, which is an average expansion of the registered projects in the “Unidad de Planeación Minero Energética” (UPME), from the Minister of Mines and Energy.

The above exercise is executed for two of the sixteen GCMs and, for each of those, two Representative Concentration Pathways (RCPs): RCP8.5 (Riahi et al., 2011) and RCP4.5 (Thomson et al., 2011). The selected GCMs are CNRM-CM5 (a dry projection for Colombia) and CESM (median projection) (Fig. 1). The resulting projections of hydropower generation under climate change are used as input to the energy models described in the following section.

2.2. Energy models

Following the framework of the Integrated Climate Modeling and Capacity Building – Latin America Modeling Project (CLIMACAP-LAMP) (van der Zwaan et al., 2016a, 2016b; van Ruijven et al.,

Table 1
Base year, data sources and structural differences between models.

Model/Feature	GCAM	TIAM-ECN	Phoenix	MEG4C
Economic coverage and feedback	Partial equilibrium	Partial equilibrium	General equilibrium	General equilibrium
Foresight and dynamics	Myopic / recursive	Intertemporal Optimization	Myopic / recursive	Myopic / recursive
Calibrated years	1990, 2005, 2010	2005, 2010	2004	2010
Endogenous variables	Prices, energy supply, energy demand, emissions	Energy supply, trade, emissions, prices (marginal costs)	Prices, energy supply, energy demand, emissions, final consumption, GDP	Prices, emissions, GDP, energy demand, final consumption
Exogenous variables	Population, labor productivity, technology cost, resource availability	End-use demand (population, GDP), technology parameters (investment costs, etc.)	Population, labor productivity, AEEI growth rates	Population, emissions factors, labor and capital productivity
Emissions data sources	CDIAC, EDGAR	EDGAR, IEA	CDIAC	CLCDS/IDEAM
Population data sources	United Nations	United Nations	United Nations	DANE
GDP data sources	UN, WB	World Bank	GTAP, PWT	MHCP
Energy data sources	IEA	IEA	IEA, GTAP	UPME/DANE

Abbreviations: CDIAC Carbon Dioxide Information Analysis Center. EDGAR Emissions Database for Global Atmospheric Research. IEA International Energy Agency. GTAP Global Trade Analysis Project. PWT Penn World Table. CLCDS Colombia's Low Carbon Development Strategy. DANE National Administrative Department of Statistics. MHCP Ministry of Finance and Public Credit. UPME Mining and Energy Planning Unit. (Calderón et al., 2016).

2016) we adopt four independently developed energy system models. These are the Global Change Assessment Model (GCAM), TIAM-ECN, Phoenix, and MEG4C (Table 1). GCAM and TIAM-ECN are partial equilibrium models whilst Phoenix and MEG4C are general equilibrium models. All represent Colombia as a distinct region. TIAM-ECN, GCAM and Phoenix can be run under climate policy scenarios consistent with the RCPs. These models have previously been used in Colombia to investigate CO2 emission scenarios as well as the effects of implementing carbon taxes and abatement targets on the energy system (Calderón et al., 2016) (See Supplementary material for more details). In contrast, MEG4C is a national model that is calibrated using data from official Colombian government sources, and has been employed to analyze the economic impacts of climate change and mitigation policies in Colombia (DNP-SDAS, 2012). Each energy model approaches climate policy simulation and power sector adaptation decisions in its own distinct way. Similar to many previous assessments (van der Zwaan et al., 2016a, 2016b; Clarke et al., 2016, 2014; Kriegler et al., 2013; Jewell et al., 2013; van Sluisveld et al., 2013; Staub-Kaminski et al., 2013; Bowen et al., 2013; Calvin et al., 2012; Chaturvedi et al., 2012), we deliberately avoid harmonizing socio-economic model inputs to capture some of the inherent uncertainty in these variables across the four energy models. The use of these contrasting models and varying socioeconomic assumptions allows us to offer a broader assessment of the implications of climate impacts on hydropower in Colombia.

GCAM (Calvin et al., 2015, 2018) is a dynamic recursive model designed for exploring implications of climate and energy policy on economics, energy systems, land use, agriculture, and water. The model applies some basic assumptions relating to socio-economic change (i.e., population growth, labor participation, and productivity) to drive demands for energy and land resources, which are balanced by retiring and adding various technology options, including electricity generating facilities. These technologies are selected according to their relative costs using a logit-choice formulation, which avoids the unrealistic situation of a single cheapest technology dominating market share (Clarke & Edmonds, 1993; McFadden, 1980). A single run spans the period 1990 – 2100, providing results in five-year intervals for 32 geopolitical regions. For the electricity sector, GCAM incorporates a variety of power generating technologies, including carbon-based fuels (conventional and integrated gasification combined cycle, with and without CCS), renewables (geothermal, the wind and solar technologies) and nuclear facilities. Hydropower is defined exogenously, meaning other technologies compete to meet the remainder of demand that cannot be met by hydropower generation. Atmospheric CO2 and radiative forcing from all emissions are computed using a reduced-form climate-carbon-cycle model, named Hector (Hartin et al., 2015, 2016).

The TIAM-ECN model (Rösler et al., 2014; van der Zwaan et al., 2013) is designed for long-term energy systems and climate policy analysis. The model is global in scope with a world energy system disaggregated into 20 distinct regions. TIAM-ECN is a linear optimization model, based on energy system cost minimization with perfect foresight until 2100. The model simulates the development of the global energy economy over time from resource extraction to final energy use. The objective function is defined as the discounted total energy system costs summed over all time periods and across all regions. The main cost components included in the objective function are investment costs and fixed plus variable operation and maintenance costs for the various energy supply and demand options, including emission reduction measures. The model utilizes a comprehensive technology database that includes a number of fuel transformation and energy supply pathways encompassing the set of possible fossil, nuclear, and renewable energy technologies. TIAM-ECN distinguishes between five hydropower investment cost classes, for very small (< 1 MW), small (1–20 MW), medium (20–100 MW), large (100–1000 MW), and very large (> 1000 MW) capacities, respectively. We assume an economies-of-scale effect between these categories, that is, specific investment costs (i.e. the costs per unit of capacity) decrease

with the size of the hydropower plant. Also, we assume learning-by-doing, in the sense that investment costs decrease, for each of the five categories, as their deployment increases (see Arias-Gaviria et al., 2017, for a justification of our hydropower cost assumptions).

Phoenix (Sue Wing et al., 2011) is a dynamic recursive model solved in 5-year time steps from 2005 through 2100 and calibrated using GTAP 7.1. In Phoenix, the world is divided into twenty-six regions, and each includes up to 34 industrial sectors. The distribution of goods in each period is based upon optimizing behavior by both the producers and consumers; producers minimize costs given a particular nested constant elasticity of substitution (CES) production technology and consumers maximize nested CES consumption given a budget constraint. The model steps through time in a myopic fashion with a constant marginal propensity to save out of households' current income determining the level of new capital formation. After each solve, capital, labor, the autonomous energy efficiency improvement (AEEI) and energy reserve data are updated. The labor productivity and AEEI growth rates are exogenous. Over time, accumulation of the capital stock, together with assumptions about region-specific rates of increase of population, aggregate labor productivity, energy intensity decline, and resource productivity, determine the simulated regions' BAU trajectories of economic output, prices, and CO2 emissions. Particular attention is paid to energy technology detail within Phoenix. There are nine electricity-generating technologies (coal, natural gas, oil, biomass, nuclear, hydro, the wind, solar, and geothermal) and four additional energy commodities: crude oil, refined oil products, coal, and natural gas. Coal gasification and liquid biomass are introduced as backstop technologies for the gas and refined oil commodities respectively. CCS technology is assumed to be available in 2020 to generated electricity from coal and gas, but with unit costs of production higher than their conventional alternatives. Primary energy data for the base year come from GTAP and IEA. Data on total fossil resource by fuel and region come, in part, from GCAM. Production is modeled as nested CES functions with energy inputs in one nest, energy then substitutes with material inputs and the energy-materials nest is combined with value added. Crude oil and gas are traded as Heckscher Ohlin goods. The remaining material and energy commodities are traded as Armington goods.

MEG4C is a single-country recursive dynamic general equilibrium model used to analyze the economic impacts of climate change and related issues in Colombia. Unlike the three other models used in this study, MEG4C is a national model and does not represent the rest of the world. It considers the different links that characterize a complex economic system so as to obtain a more complete picture of the consequences of climate change, and both develop and apply better public policies. It allows for the analysis of economic consequences of climate change (BID, CEPAL, DNP, 2014). It is based on the GREEN model (General Equilibrium Environmental Model) developed by the OECD to quantify the effects of policies to reduce GHG emissions (Bourneaux et al., 1992). As a traditional CGE model, MEG4C applies neoclassical economic theory. As such, the decisions of agents (sectors and households) stem from a cost minimization and consumption maximization process, and prices are assumed flexible to ensure equality between supply and demand in the market for goods and factors of production. It assumes no substitution within the goods in the intermediate consumption bundle and between it and the value added-energy bundle. In the other stages of production, the substitution possibilities are modeled using a Constant Elasticity of Substitution (CES) production function. The model includes five current electricity-generating technologies (coal, natural gas, oil, hydro) and is calibrated using UPME data.

The global energy models used in this study can be operated assuming a world in which emissions reductions are pursued to stabilize radiative forcing at 4.5 W/m2. This is a crucial feature that allows us maintain consistency between the RCP pathway adopted in the input climate projections and the assumptions that influence energy sector investments in each scenario (see Experimental Setup). GCAM simulates RCP4.5 as a cost-minimizing pathway in which all world regions undertake emissions mitigation simultaneously and effectively (Thomson et al., 2011). A global cost on carbon drives changes to the energy system—including the deployment of low-carbon electricity generating technologies—to stabilize radiative forcing at 4.5 W/m^2 before 2100. In Phoenix, the policy scenarios are implemented through a global CO_2 constraint that was created to match cumulative CO_2 emissions for the RCP 4.5 W/m^2 target under Shared Socioeconomic Pathway 2 (Riahi et al., 2017). The inter-regional trade of emission permits is allowed under the policy scenarios, producing one, global carbon price. TIAM-ECN calculates policy scenarios by minimizing the total global energy system costs under a set of pre-defined constraints, in this case through the imposition of a limit to the value of the additional radiative forcing (RCP4.5 with a maximum of 4.5 W/m^2) associated with an anthropogenically increased concentration of GHGs in the atmosphere (see e.g. Kober et al., 2014). With TIAM-ECN we only represent the three main Kyoto gases (CO2, CH4 and N2O). MEG4C is a single country model often used for policy analysis in Colombia by the National Planning Department (Alvarez-Espinosa et al., 2014). For this reason, MEG4C cannot run the policy scenario, and instead climate impact on hydro power pass through to the model as a sectorial impact

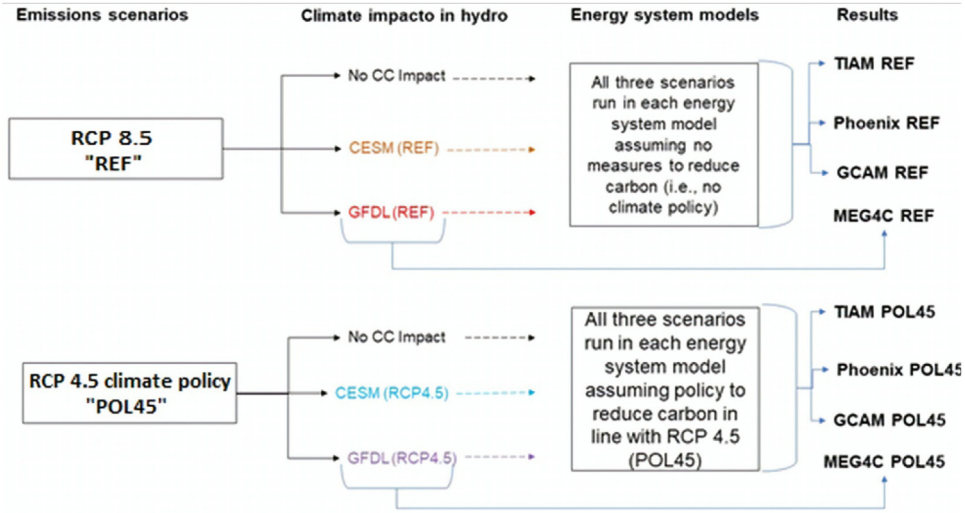

Fig. 2. Experimental setup.

over hydro power sector (see Fig. 2). Thus, it considers the different links that characterize a complex economic system so as to obtain a more complete picture of the consequences of climate change, and both develop and apply more informed public policies.

2.3. Experimental setup

The experimental approach is designed to align hydropower impact projections (Fig. 2) with the policy being simulated. For the reference scenario ("REF"), all energy models are operated assuming a world in which carbon emissions are unconstrained—that is, there is no price on carbon and so little incentive to invest in low-carbon power generating facilities. Since emissions are not curbed, climate impacts are explored using hydropower production estimates generated assuming RCP 8.5. For the policy scenario ("POL45"), the global energy models are operated assuming a world in which emissions reductions are pursued to stabilize radiative forcing at 4.5 W/m^2. Here, climate impacts are explored using hydropower production estimates generated assuming RCP 4.5. The experimental setup thereby accounts for feedback between the carbon policy being pursued and the climate forcing applied to the hydropower model (Fig. 2). Additionally, a baseline case (no climate change impact) is assessed, providing a benchmark to isolate impacts of climate on the power sector under each policy scenario. In total, we therefore run six scenarios using four energy models (i.e., 24 runs).

3. Results

3.1. Power sector composition under climate change and mitigation policy

The composition of electricity generation in Colombia varies widely across the energy models and RCPs, but much less so across the three climate projections considered (Fig. 3). Even under the dry climate projection with RCP8.5 (REF_CNRM), results are almost indistinguishable from the REF case—highlighting a much more important role of technology costs and policy influence on expansion decisions for the immediate planning horizon. For the reference cases, the energy models differ only marginally. Both TIAM-ECN and Phoenix expand primarily into coal to meet growing power demands. GCAM follows steeper upward trajectory of total output with most expansion coming from gas, but the general trend and dominance of fossil technologies is consistent across models. Since planned hydropower expansion fails to keep up with demand growth, the share of hydropower (as a percentage of total output) falls substantially in all cases. For example, GCAM increases the share of fossil fuel technologies from 28% in 2015 to 67% in 2050 (Coal 17% and Gas 50%) while the share made up by hydropower declines from 60% to 26% in the same period. All three global models indicate that hydropower will lose its dominant share of Colombia's power generation over the next three decades under RCP 8.5.

The most distinct differences across the models are observed under the policy cases. These differences are attributed in part to differences in the underlying structure of the energy models; MEG4C is a computable general equilibrium model (recursive dynamics) while GCAM is a partial equilibrium model (dynamic optimization), for instance. There are also differences in the models' process resolution as well as technology representations, and cost and trade assumptions. In addition to the structural uncertainty associated with energy models, variations could also arise from the lack of harmonization in population and GDP inputs across the four energy models (as noted earlier, this was by design to capture the inherent uncertainty stemming from using different energy models). As shown in Fig. A1, the population projections are somewhat consistent, but there are some variations in economic growth projections across the four models. However, this should mainly affect the scale of energy system, so much of the variation in term of the prevailing adaptation strategy is driven by the variations in the energy model structure, technology and cost variations. For example, the

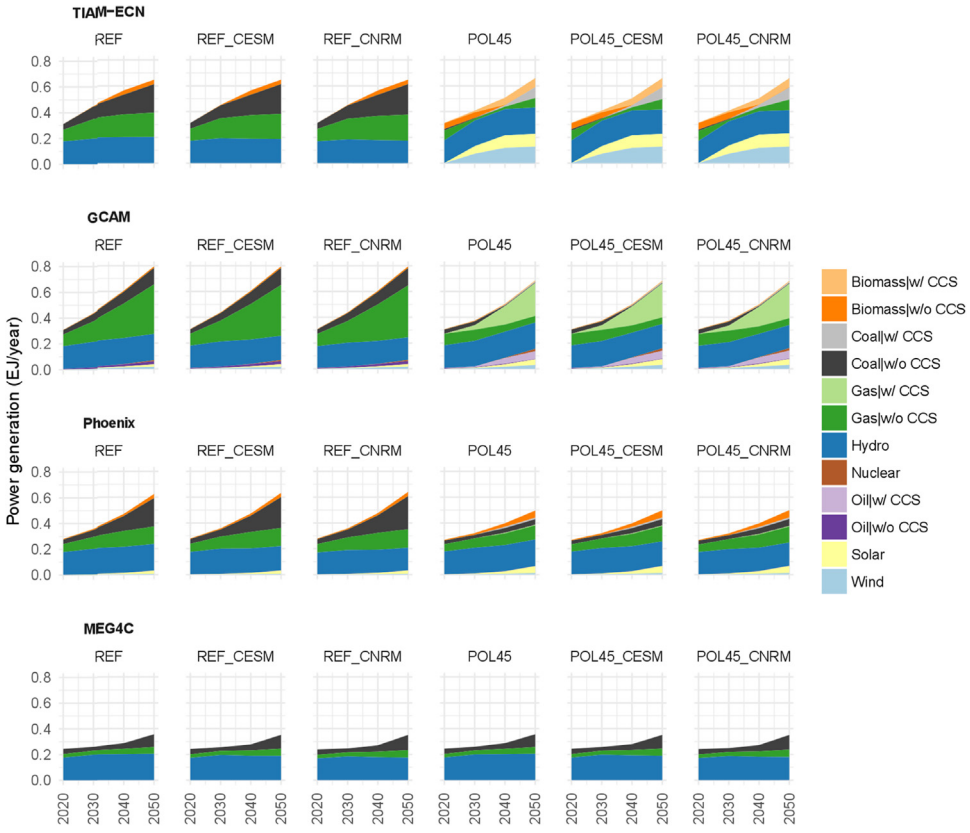

Fig. 3. Electricity generation by source in Colombia, 2020–2050.

TIAM-ECN model responds to policy by replacing fossil fuels with solar and wind in similar proportion (~40% generation from solar and wind by mid-century for POL45), whilst GCAM and Phoenix expand far less in solar and wind (< 10% total generation by mid-century for POL45) and instead rely on demand reduction and expansion of gas-fired plants with CCS. This model discrepancy reflects conservative estimates for wind and solar potential and cost in Colombia relative to conventional technologies with CCS. The prevailing decarbonization strategies for the GCAM, TIAM-ECN, and Phoenix models are consistent with earlier studies (see Calderón et al., 2016), and are generally intrinsic to the underlying nature of these models. The results herefore highlight that it is important to apply multiple energy models in energy policy analyze—in the same way as the common practice of applying multiple climate models to climate change impact studies. Similarly, planners will need to understand the implications of climate change uncertainty on future infrastructure investment decisions. Planners will also need to understand the inherent uncertainties arising from technological cost assumptions, too.

Even though the impact on future energy composition of policy (REF versus POL45) far outwights that of climate change (no impact versus CESM and CNRM), the impact of climate change on the hydropower generation in Colombia is non-trivial. Under the dry scenario (CNRM), climate change reduces hydropower generation by ~ 10% by 2050. Technologies deployed to replace climate-driven shortfalls (Fig. 4) reflect the technologies deployed to meet growing demands for power (Fig. 3). Under the REF scenario, the models replace lost hydropower with additional generation from coal and gas. Phoenix relies primarily on coal, whilst GCAM relies primarily on gas to replace hydropower; TIAM-ECN expands both in equal measure. For both policy scenarios and for all models, the need for replacement generation in the dry climate (CNRM) is roughly double that required in the moderate climate (CESM).

These technological pathways can help to identify and expose potential planning issues that may arise as Colombia expands its power sector. For example, the implementation of CCS observed with GCAM – a technology that is still limited in its large scale commercial deployment – also implies increasing demand for water (Macknick et al., 2012; Hejazi et al., 2014, 2015) although a recent study has suggested that extensive deployment of CCS does not substantially increase the water requirements of electricity generation (Brandl et al., 2017). The CCS-related increasing water demand is potentially problematic because dry climate conditions also coincide with less water availability for the power sector (e.g., thermoelectric cooling) and for other water users in the economy, such as irrigated agriculture and domestic uses, thereby further increasing the vulnerability of the power sector to water shortage. For example, policies that favor bioenergy crops and fossil-CCS options can result in larger footprints on the water sector (Hejazi et al., 2015; Liu et al., 2014), which in return can affect the amount of water that is available in streams to generate hydropower, which could in turn exacerbate the impact of climate change on hydropower. Future research must search beyond the economic competition among technologies to assess the potential water and land footprints of the power sector under the various adaptation strategies. Furthermore, in this study we only focus on the impact of climate change on hydropower production, but climate change can also impact both energy demand (heating and cooling energy demands) and other energy supplies (e.g., wind, solar, biomass) as well as other sectors which in return impact the power sector (e.g., crop productivity, water supply). Future research should therefore also account for combined climate impacts across multiple sectors when assessing climate impacts on the power sector (Table 2).

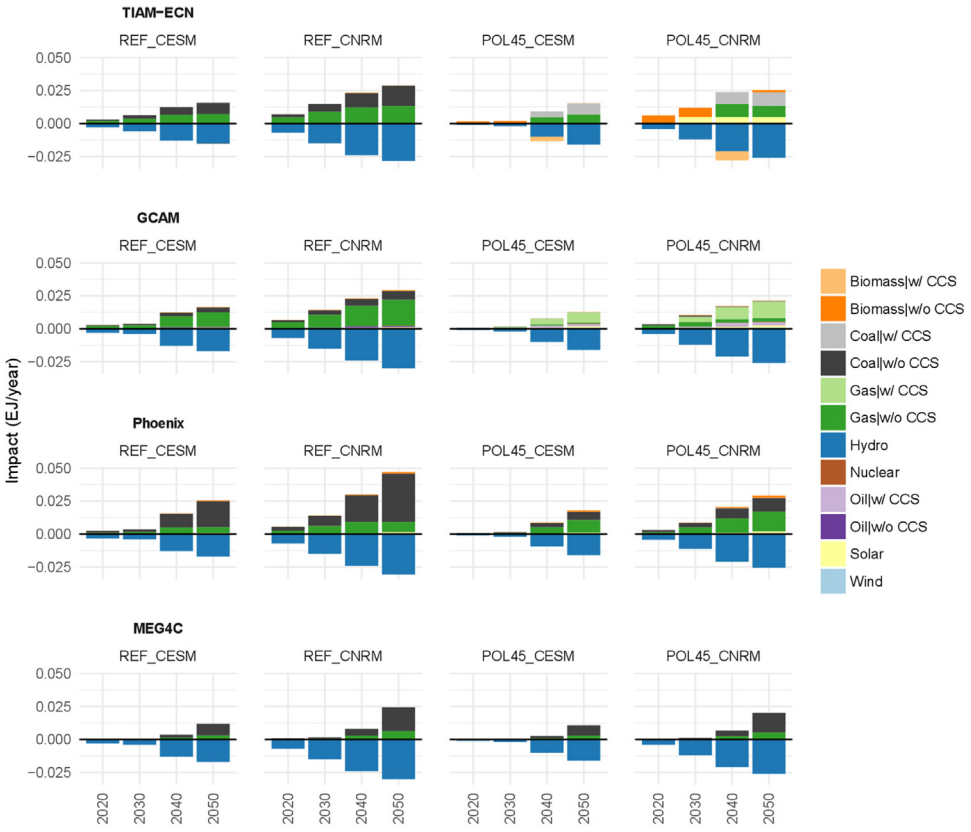

Fig. 4. Hydropower generation loss and replacement by other technologies (units in EJ / yr). REF_CESM and REF_CNRM results are relative to REF, whilst POL45_CESM and POL45_CNRM are relative to POL45.

Table 2
Projected electricity sector generation shares (%) across energy models.

	GCAM			TIAM-ECN			Phoenix			MEG4C		
	Coal	Gas	Hydro	Coal	Gas	Hydro	Coal	Gas	Hydro	Coal	Gas	Hydro
2015	7	21	71	6	21	72	11	23	66	22	12	66
2020	11	29	57	14	29	57	13	22	64	16	11	72
2030	13	37	46	22	34	45	15	26	57	11	12	77
2040	15	45	34	29	33	38	26	27	44	15	14	70
2050	17	50	26	36	31	33	37	23	35	28	15	57

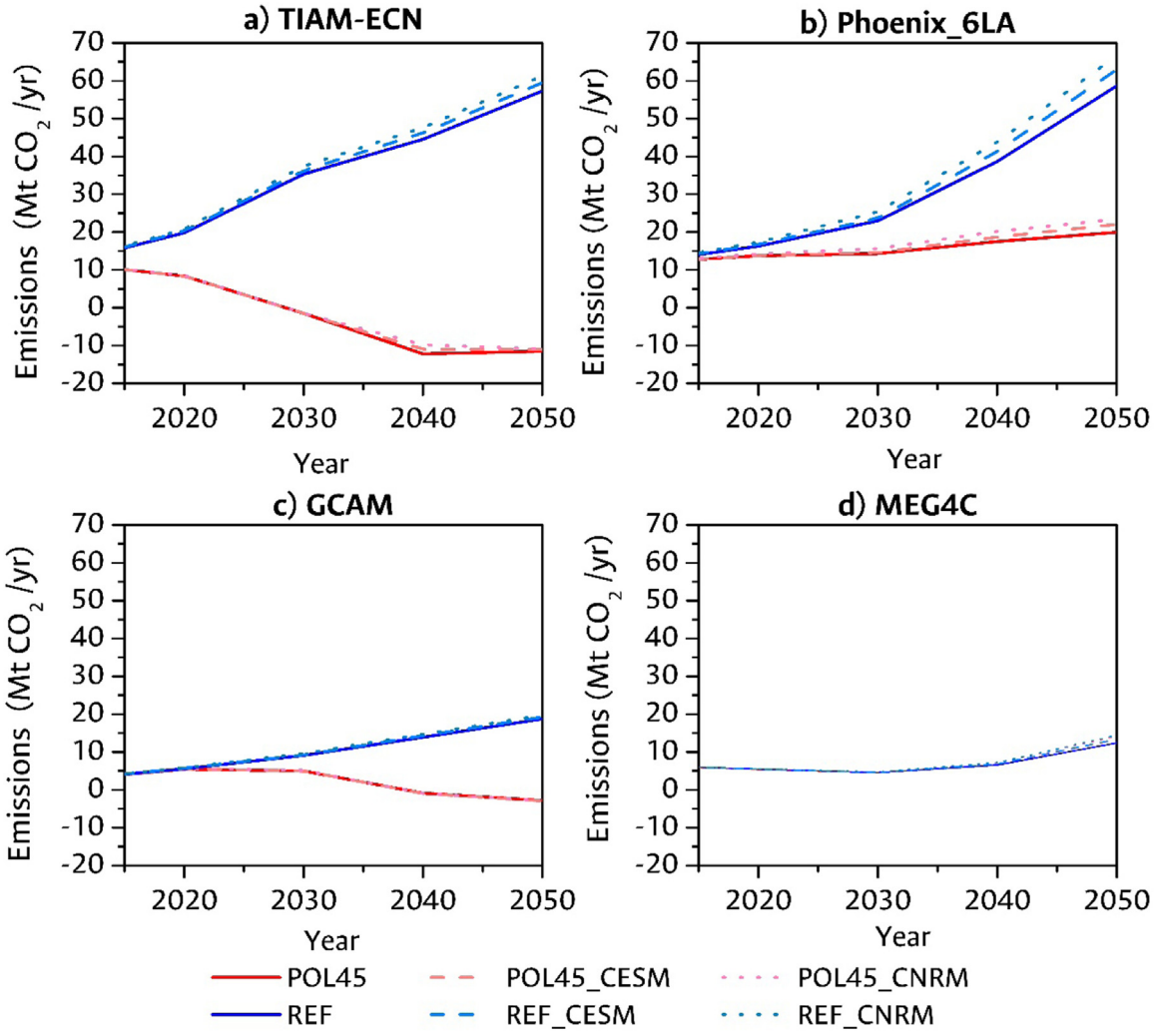

Fig. 5. Total power sector CO_2 emissions in Colombia until 2050.

3.2. Impacts on emissions and the Colombian economy

Population and GDP growth drive increased electricity consumption across all models. This coincides with growth in CO_2 emissions from the power sector if no climate change mitigation policy is implemented (Fig. 5). The expansion in power sector CO_2 emissions under the REF scenario for all models is a consequence of the diminishing role of hydropower relative to fossil fuels. Under the REF scenario, climate change drives up CO2 emissions, but only modestly (less than 2–3% by 2050 under the dry scenario for Phoenix and TIAM-ECN; negligible impact for GCAM). The impacts are far less pronounced under RCP4.5—an expected result, since the replacement technologies are low-carbon. Climate policy has a far greater impact, reducing power sector CO_2 emissions drastically in all cases. In the case of GCAM and TIAM-ECN, power sector emissions become negative before mid-century, owing to increased generation from biomass with CCS. Emissions in Phoenix track the downshift in overall power generation. The small increase in CO_2 emissions associated with accounting for climate impacts on hydropower is partially explained with the assumed availability of alternative low-carbon technologies in Colombia. In reality, these technologies may not be feasible. For example, Colombia is the world's fourth largest coal exporter and Latin America's fourth largest oil producer, but the realization of such scenarios would hinge on the successful penetration of the CCS-based technologies (biomass, gas, oil and coal), which are known to have large water demand implications. Similarly, Colombia has considerable potential for the development of other renewables, including wind in the northern region, solar in the Guajira peninsula, and geothermal power in the South. The government

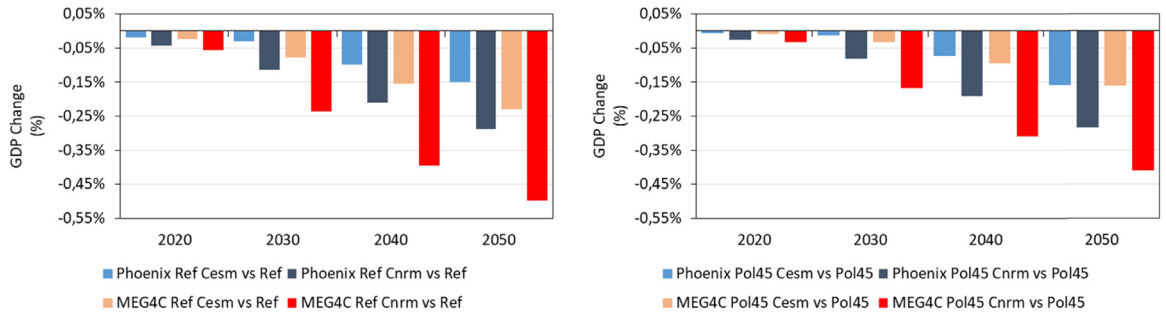

Fig. 6. GDP change relative to the baseline for policy (left) and no-policy (right) scenarios (GDP in billion US$(2005 / yr).

of Colombia aims to achieve 6.5% of production from non-hydro renewables by 2020 by enacting a new renewable energy law (Law 1715) intended to mobilize investments through various tax breaks. However, achieving the penetration of other nonrenewable might be hindered by a gap in investments in transmission infrastructure. The ability of other alternative technologies to make up for the lost hydropower resources will depend on a multitude of institutional and economic factors such as those described above.

Both Phoenix and MEG4C represent economic variables endogenously, and can therefore be used to add to earlier work demonstrating potential GDP losses of ~2–3% by 2050 resulting from climate policy implementation (Calderón et al., 2016). These models indicate increasing prices for coal as domestic coal demands increase, leading to a decrease in coal exports. These shifts in demand and trade continually lower Colombia's GDP, such that by 2050 the impact could be 0.15% below reference levels in the CESM REF case to 0.28% in the CNRM POL45 case. This result on GDP does not consider other impacts associated with climate change such as the reduction in crop productivity, milk and meat production that are equal to 0.49% of annual GDP (BID, CEPAL, DNP, 2014) (Fig. 6).

4. Conclusions and policy implications

Colombia's power sector is currently dominated by hydropower, which may change as power demands increase at a faster rate than new hydropower capacity is installed. New power plants from non-hydropower technologies will be needed to sustain a growing population. This study finds that Colombia's path of power sector adaptation will be largely defined by its approach to climate change mitigation strategy. If we assume that Colombia participates in global efforts to stabilize radiative forcing at 4.5 W/m2, there are various technology pathways the country could implement to provide sufficient power to meet demands. Three of these pathways are identified in this analysis. The TIAM-ECN model suggests that expansion of wind and solar is feasible and may be more cost effective than relying on conventional fuels complemented with CCS. Results for GCAM counter this projection and suggest that expansion of fossil resources—primarily natural gas—with CCS may be preferable economically. A third pathway of demand reduction is identified by Phoenix and MEG4C. This is consistent with other analyses; General Equilibrium Models tend to deploy more savings and efficiencies than Partial Equilibrium Models (van der Zwaan et al., 2016a).

Technological change in Colombia's power sector will depend not only on markets and economics but also on financial, institutional, and regulatory constraints that are generally too uncertain or complex to incorporate in global energy models. Weak institutions may restrict access to loans and technology and prohibit adequate investment in infrastructure in developing and rural regions (Hertel and Lobell, 2014). For example, the Colombian government is currently in the process of adopting a new renewable energy policy to allow for the expansion of renewables by eliminating barriers, and analyzing possible incentives and subsidies programs, including tax reduction, feed-in tariffs, tradable green certificates, and technical subsidies (Arias-Gaviria et al., 2017; Arias-Gaviria et al., submitted for publication). Thus, to understand the viability of the different adaptation strategies, accounting for the regulatory dimension and how existing policies and regulations may hinder or promote their effective penetrations is essential.

Climate change impacts on hydropower generation are relatively modest, but not negligible. In a world in which measures to curb CO_2 emissions are absent, climate change could deteriorate hydropower production by approximately 15% by 2050 (dry scenario). This would shift power demands onto more carbon intensive resources, increasing Colombia's CO_2 emissions from its power sector by up to 3% by 2050. There is substantial uncertainty as to how this might affect economic growth, but results suggest that climate-driven losses in hydropower could reduce 2050 growth rates by up to 0.28% assuming the dry scenario. Follow-on work from this study could investigate the general temporal mismatch of demands and supplies in term of electricity and water demands and water resources availability during the different seasons within a year, which generally requires linking up with more detailed energy and hydrologic models (see for example, Voisin et al., 2016). Follow on work could also examine further the potential impacts of climate change on other aspects of the power sector, such as wind and solar resources, cooling water for thermal generation, water demand for CCS, and heating and cooling demands for buildings. Combining these impacts in a single assessment may be a necessary advance for understanding compound impacts—effects that emerge only when multiple simultaneous impacts on a system are assessed in combination. Other important factors, such as water allocation across multiple sectors, are already being incorporated into global, interdisciplinary assessment models. Such advances will help broaden and deepen the significance of the analysis, and provide the means to address a burgeoning set of science questions concerning the planning and management of coupled human-natural systems adapting to climate change and climate mitigation policy.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2018.12.057.

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